OPEN CHANNEL FLOW MONITORING

UNDER SMALL WATER SURFACE GRADIENTS

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INTRODUCTION

A flow monitoring network was established as an integral part of a study to evaluate the effectiveness of on-site detention of agricultural runoff on nutrient loading in the Kissimmee River Valley of South Florida (4). The project was a joint effort by several state, regional, and federal agencies (4). The monitoring network consists of twelve flow measuring sites at five hydrologically distinct watersheds (5). The locations of the five watersheds and the types of flow measurement used at these watersheds are given in Figure 1. Primary emphasis in selection was on obtaining a proper range of conditions for evaluating water quality parameters. This policy resulted in the selection of several sites which had very poor characteristics for the measurement of flow. These "poor" sites are characterized by very flat water surface gradients (less than 1 foot/mile) often operating under backwater conditions, wide shallow heavily vegetated channels, very low velocities (less than 0.1 foot/second most of the year), and severe restrictions on not aggravating flooding conditions upstream of the sites. Due to poorly drained conditions at most sites water remains in the channel most of the year, but flows are too small to be measured except for 30 - 60 days per year.

A major objective of the study was to quantify nutrient loading generated in the watersheds. Critical depth flumes (1,3) were designed, constructed and instrumented to match the accuracy of the measured flow with that required for nutrient loadings. Existing structures, particularly culverts with flashboard risers, were used where possible to hold down costs and provide operational flexibility in spite of a reduction in expected accuracy. This paper deals primarily with the design and instrumentation for the five flumes constructed in the area investigated.

DESIGN PROCEDURES

An analysis to determine which portion of the expected flow range was most critical to the problem of determining nutrient loading (concentration times flow rate) was performed. A preliminary analysis of existing water quality data indicated that for agricultural watersheds in this area, the time variation of the nutrient concentrations was small in relation to the time variation in flow and thus could be neglected in designing the flow measurement facilities. A modified flow duration (8) analysis was performed on a stream in the general area on which flow records had been kept for over 20 years. Flows were divided into discrete ranges, and the number of days the average daily flow fell into each of the ranges was tabulated. The number of days of flow in each range was multiplied by the average flow rate in each interval. This allowed the computation of the percentage of the total flow which could be expected to fall in each flow range. When scaled to the size of the drainage area, a clear picture of which flow ranges were most critical was obtained. The flow duration curve is presented in Figure 2.

From this analysis it was concluded that nearly 90% of the flow could be expected to fall in the range of .02 inch/day to .75 inch of runoff per day. The range, .02 to .10, was the most critical in terms of total nutrient loading. This approximation was used to establish the most critical flow range. Thus more emphasis was placed on low flow measurement, (at an acceptable sacrifice of accuracy in measuring the rare high flow events) than in most open-channel flow monitoring systems. For economic reasons the facilities were designed such that large flows would partially bypass the measuring facilities. The design flow range varied from 5 - 200 cfs at the largest measuring site to .25 - 10 cfs at the smallest site. These flow ranges are equivalent to .02 - .75 inches per day runoff.

Critical depth flumes, in conjunction with low levees that constricted the flow area, were

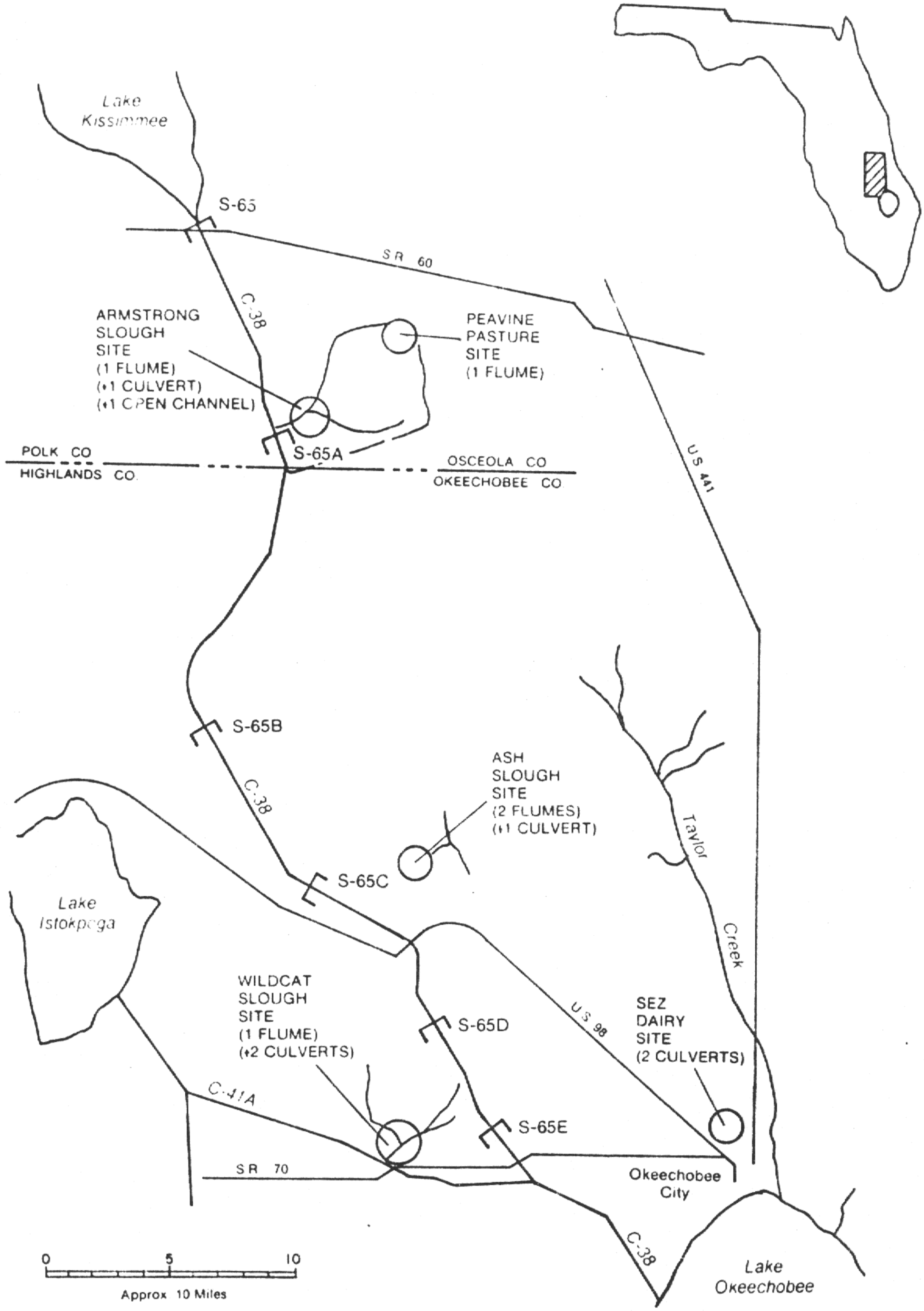


Figure 1 STUDY SITES UPLAND DETENTION/RETENTION DEMONSTRATION PROJECT

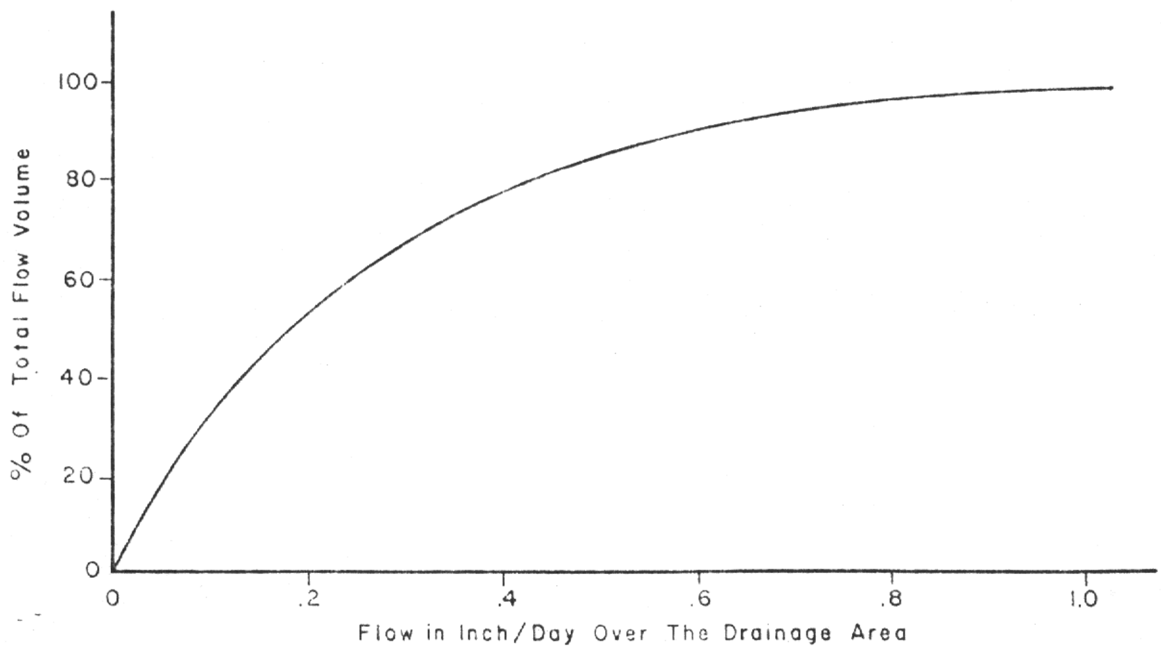


Figure 2 % OF TOTAL FLOW CONTRIBUTED BY FLOW RATES LESS THAN GIVEN FLOW RATE selected for the most difficult sites. Replogle (7) has demonstrated the major advantages of this measuring device, namely: flexibility in design characteristics, low backwater effects, and provision for adjusting the rating curve for construction deviations without expensive or impossible field calibration. A computer program developed by this investigator (7) will accommodate a wide range of shapes and design characteristics. This program will keep calibration error to $\pm$ 2 or 3% in the design flow range after construction deviations are accounted for in the program. Minor modifications were made in this program to improve convergence characteristics in the low flow range and accommodate computer input-output to local requirements.

With this program available it is very easy to determine the effects of changes in structure size and shape on the stage-discharge relationship. A trial and error procedure was used for preliminary determination of size and shape. Standardization to simplify construction procedures was a major goal. The criteria used was that backwater caused by the structure should not be in excess of 0.5 foot at flows of 0.75 inch per day and backwater effects would diminish at larger flows. Side slopes of one vertical to two and one half horizontal and a sill length of three feet were selected. An iterative process was then used for each site to refine the sill height and sill width using the values found above to obtain the proper sensitivity and insure that backwater effects would not be excessive.

Sensitivity was determined assuming resolution in stages to be on the order of .002 foot with questionable reliability when the flow depth over the sill was outside the range of 0.05 - 0.5 times the sill length or the depth over the sill is greater than 75% - 85% of the downstream depth over the sill. These limits were selected more or less arbitrarily from criteria presented by Replogle (7). One unusual storm event produced flows with submergence ratios in the range of 80 - 90% and flow depths over the sill of .6 - .7 times the sill length. Computed flows from this event appear very reasonable when they are compared with flow at neighboring locations, water budget checks, and approximate stage discharge relations downstream of the measuring sites indicating that for these particular structures computed flow may be as good as other approximate methods (say $\pm$ 30 - 40%) even in the questionable range. For design purposes, the downstream depth over the sill at a given flow was estimated by observing the flow in the natural channel at several flow points in time and fitting to a power curve of the general form $Q = K1 * (STAGE - K2)^{K3}$, where Q = discharge in cfs, "stage" is the stage in feet, K1 is a constant, K2 is a constant corresponding roughly to the stage at zero flow, and K3 a constant on the order of 1.5 to 2.8 integrating the effects of changes in cross sectional area and flow resistance with flow depth. Considerable judgment and experience were required for estimating these coefficients since hydrologic conditions permitted obtaining only 3 or 4 measurement points. Since the structures were designed to provide minimal obstruction of flow under given hydrologic conditions the downstream stages could be approximated by the stage-discharge relation prior to installation of the structure.

Several observations on structure shape were made. In general: (1) making side slopes flatter causes submergence at lower stages and decreases backwater effects at high flow rates (providing sill width is not too large) while decreasing sensitivity, (2) raising the sill height increases the value of flow at which submergence occurs and increases backwater effect but has little influence on sensitivity, (3) decreasing sill width increases sensitivity and increases backwater effects. Figure 3 indicates the general shape characteristics selected.

In order to provide water level resolution on the order of 0.002 foot the recorder and sensor must be carefully selected. An instrumentation and economic analysis of currently used methods of collecting and processing stage information indicated that substantial savings could be realized by using digital paper tape punch recorders with float operated sensors. Data processing costs were considerably less for digital instrumentation. Digital punch recorders most commonly used have a range of 0 to 99.99 feet. Several manufacturers were willing to provide the recorders with a range of 0 to 9.999 feet (or its nominal metric equivalent) providing resolution of 0.001 foot or .001 meter at approximately the same cost as the more common range.

Float operated sensing devices need special consideration when resolution to this scale is desired. Friction and inertial effects become important on this scale (2,6). Fortunately, most of these effects can be reduced by proper stilling well design and the use of larger than normal floats. A 14 inch float was selected for use with these recorders. It is expected that sensitivity can be maintained at 0.002 foot with careful recorder maintenance and at .005 foot with normal maintenance procedures. Problems in registering the recorder punch datum in reference to sill elevation closer than 0.01 foot have been encountered. Several procedures to improve this situation are currently being analyzed, but conclusive recommendations are not yet available.

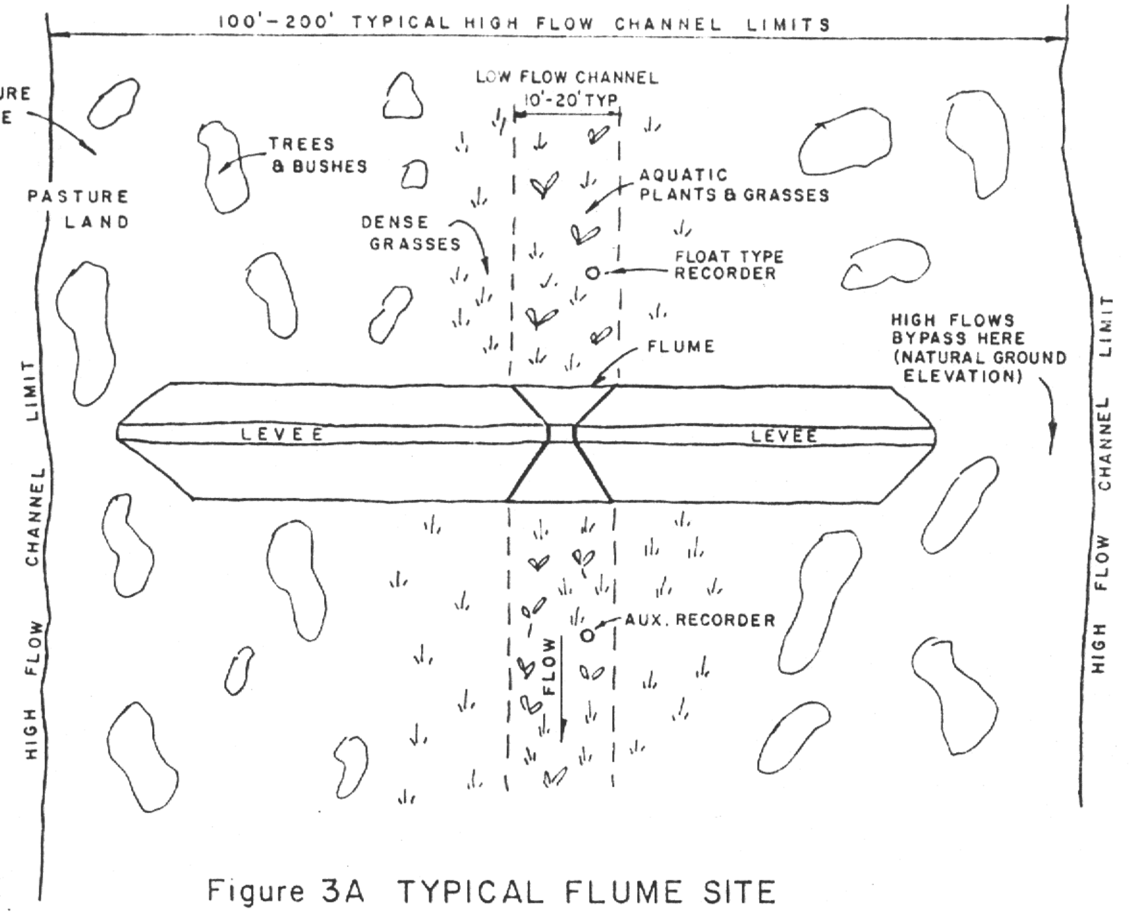


Figure 3A TYPICAL FLUME SITE

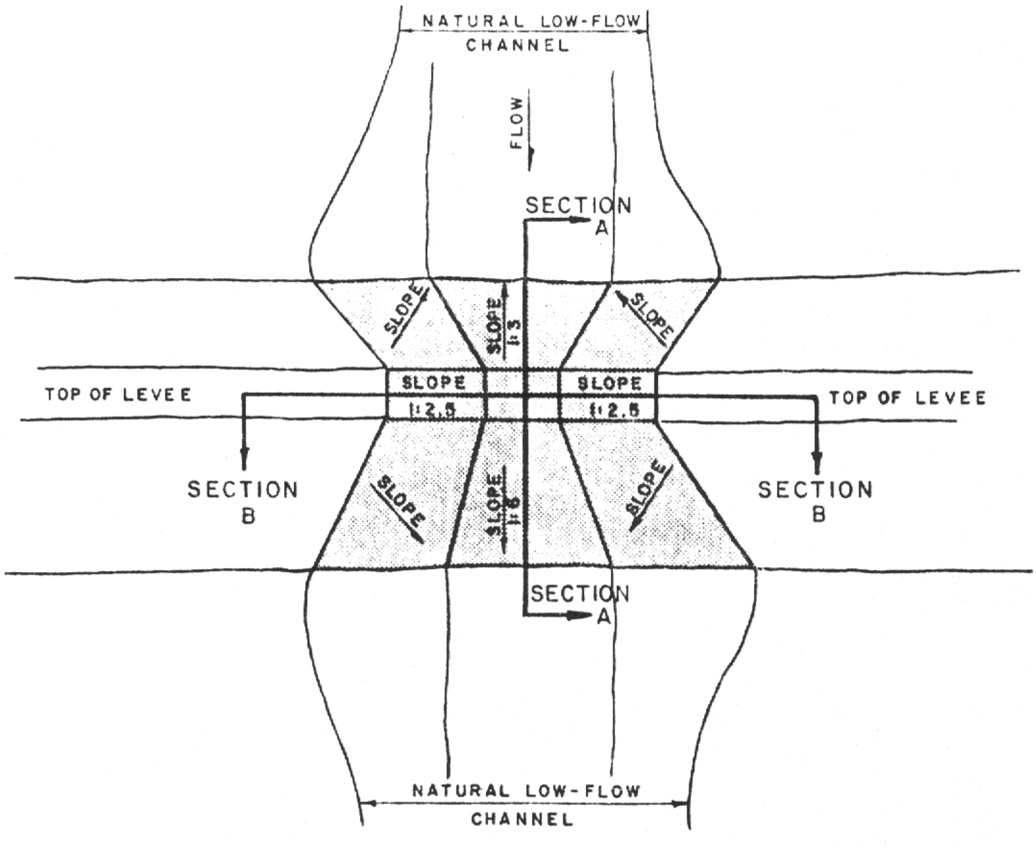
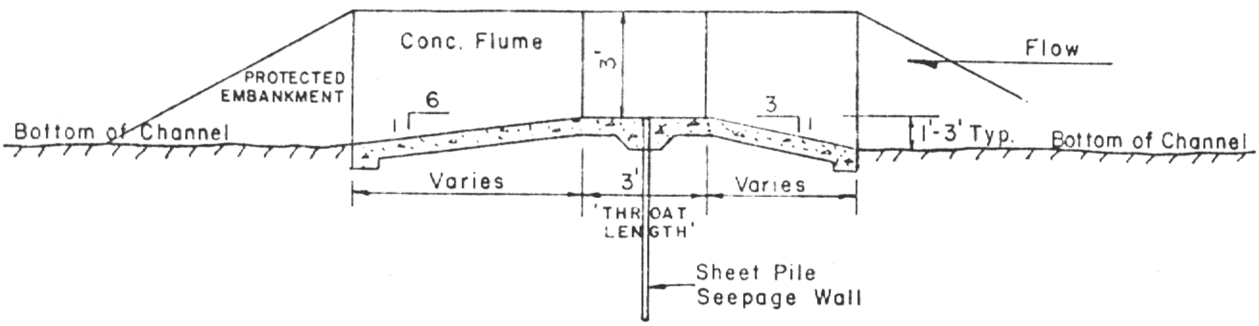


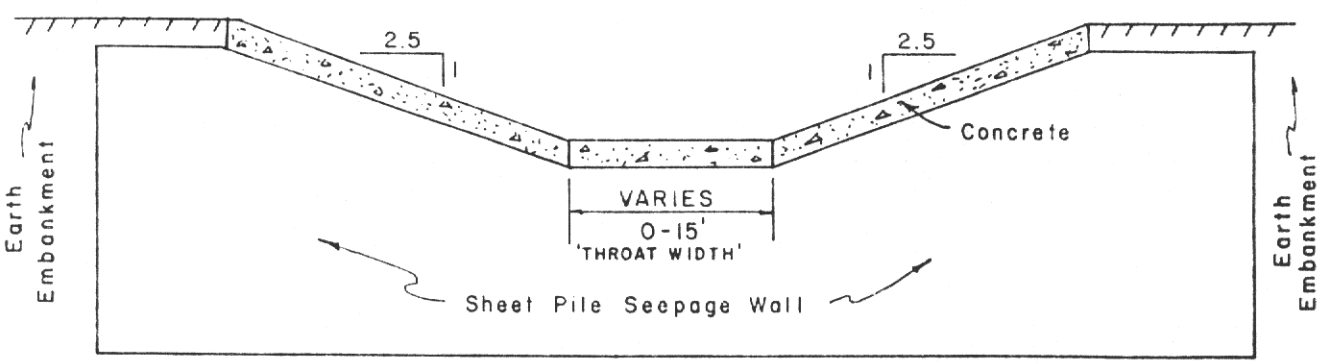
Figure 3B PLAN VIEW OF TYPICAL FLUME



SECTION A

TYPICAL SECTION THROUGH FLUME IN THE FLOW DIRECTION

Figure 3C



SECTION B

Figure 3D

INSTRUMENT SPECIFICATIONS

A governmental agency must purchase recording devices by bid which results in some uncertainty in the physical characteristics of the device that will finally be used. Certain details were highlighted in the request for bids as well as the general description of the intended use of the sensor-recording devices. These are outlined below with a description of the reasoning that required their inclusion.

a) Instrumentation to be field located. Possibly unattended for thirty days or more. No line power available. Suitable for reliable operation in a light sheet metal housing. A survey of suppliers/manufacturers indicated that instruments were available to operate on a single 7.5 or 12 volt dry cell battery for 60 days or more. The 7.5 volt version was decided upon to reduce the possibility of theft (fewer lanterns etc. use 7.5 volts than 12). A light weight dust and dirt cover was supplied as a part of the instrument. This assembly was placed in a light weatherproof sheet metal housing fabricated separately to District design.

b) Stages to be recorded on four channel BCD paper tape (no decimal point) at selectable preset intervals. The sensor (14 inch diameter float) movement to have a range of 0.000 to 9.999 units with the capability of roll over. This punch format was picked since readers were available that would interface with our existing automatic data processing equipment. The range of 0 to 9.999 units becomes critical when the requirements of the flow device are recalled. The bidders offered, as standard items, the above units range in either metric or English units. The last digit in the metric system is equivalent to 0.0033 feet or slightly over 1/3 of the resolution of the English system. This was considered acceptable in light of required accuracy. The successful bidder supplied the English system.

c) The recorder punches a record of the float position at selectable intervals. A field evaluation of water level change rates for the selected sites were made. This evaluation indicated that a half hour interval would provide a sufficient number of data points to suitably define water level fluctuations. Solid state timers with interval settings of 5 minutes to one hour in 5 minute intervals with low standby current drain were offered (one bidder used one minute increments to over one hour). Mechanically driven timers were also available. The adjustable solid state timer was selected over a mechanical system to allow ease in making a field change to punch interval. The half hour interval as originally selected has provided satisfactory results without noticeable bias in the resulting discharge indications. Recorder torque to be overcome by the float type sensor and timing interval led to the use of the 14 inch diameter float. The stilling well attenuation was estimated, but during installation more holes than calculated were punched in the 18 inch I.D. spiral aluminum pipe used as a stilling well. This was done to allow for obstruction of the inlet holes by debris and silt. The wells were constructed with a sealed bottom deep enough to provide for sediment deposits.

The recording stations have provided satisfactory results. The battery life often exceeded a year instead of the anticipated three to four months life. The major difficulty encountered was vandalism. One site required bullet proofing.

DATA PROCESSING AND VERIFICATION

Digital stage tapes are punched at 30 minute intervals. These tapes are collected on a monthly basis, processed through a widely used reader, and stored temporarily on magnetic tape. A special input program is used to provide a basic set of checks and insert comments prior to storage on a permanent disk file. Flows are then computed for each upstream stage data point by using a modification of the program referenced previously and stored along with flags indicating data quality.

Flags include an indication of when the measured flows are in the questionable low flow range, when submergence is likely (as indicated by a downstream recorder), as well as an indication of missing, questionable or estimated data. The downstream recorder is not required for flow computations but was included because of uncertainties in the establishment of the design conditions for submergence. In addition, the downstream recorder provides a measure of redundancy that is useful in estimating missing record.

Computed flows are checked by a water budget approach. In this procedure, flows, stages, and rainfall are used as defined quantities. The residual error terms (ET, seepage, and unaccounted storage changes) are scanned for excessive variation or long term trends.

Other diagnostic and checking routines were used, particularly for the stations at which culverts were utilized. Special plotting routines to overlay stage and/or flow hydrographs are useful in detecting datum changes, malfunctioning stage instrumentation, and unlogged changes in control elevations. Double mass curves (8) are a rapid means for checking changes in rating curves and certain types of errors which tend to bias results (such as gaps between stop logs in the culvert risers causing abnormally large leakage). Cross correlation of stage data is particularly useful in estimating missing data.

ERROR ANALYSIS AND OPERATING EXPERIENCE

Insufficient error analysis has been completed to date to adequately place limits on overall accuracy. In general, the flumes appear to be functioning satisfactorily. Observation of flow conditions at the extreme limits of the design operating range indicates that reliable data can probably be obtained well beyond the upper and lower design limits. A program has been initiated to verify portions of the rating equations for the flumes by conventional current meter techniques. Insufficient measurements have been obtained as of this date, to make positive statements on the results of this verification method.

The majority of difficulties encountered resulted from inexperienced field personnel and underestimating forces on the stilling wells during extreme storm events. The first significant runoff event was an unusually large storm. This caused severe scouring in the vicinity of stilling wells anchored in fine sand channels resulting in failure of the stilling well support system at several sites. Changes in tape readings referenced to structure datum resulted from inexperienced field personnel adjusting the recorders and stilling wells. Most gaps in information were short and monitoring redundancy was adequate to place reasonable estimates on missing or garbled data.

Design assumptions were verified within reasonable limits, except for the failure of one flume structure. This structure failed due to extremely large flow caused by drainage basin limits shifting severely during a storm with unusual areal distribution.

Culverts with flashboard risers caused the most difficulties. Boards were often inserted or removed without recording the time and amount changed. Frequent inspection by trained personnel helped narrow operational uncertainty. Some of the checking procedures also helped in identifying operational changes.

Overall confidence limits, including missing or garbled data at the 90% confidence level, are expected to fall well within 30% for the culvert flows and 10% for the flume flows.

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